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Rover Autonomous Integrity Monitoring of GNSS RTK Positioning Solutions with Multi-Constellations

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Biography

Jun Wang holds BSC from Wuhan University and MSC from Chinese Academy of Surveying and Mapping, P R China. Currently, Jun is a PhD candidate of Queensland University of Technology (QUT), Australia, researching data processing of multiple GNSS systems and signals under the financial support of China Scholarship Council (CSC) and Australian Corporative Research Center for Spatial Information (CRS-SI) scholarship programs. His research focuses on GNSS ionosphere modeling and integrity determination in real time kinematic positioning using multiple GNSS systems.

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Abstract

This paper studies receiver autonomous integrity monitoring (RAIM) algorithms and performance benefits of RTK solutions with multiple-constellations. The proposed method is generally known as Multi-constellation RAIM -McRAIM. The McRAIM algorithms take advantage of the ambiguity invariant character to assist fast identification of multiple satellite faults in the context of multiple constellations, and then detect faulty satellites in the follow-up ambiguity search and position estimation processes. The concept of Virtual Galileo Constellation (VGC) is used to generate useful data sets of dual-constellations for performance analysis. Experimental results from a 24-h data set demonstrate that with GPS&VGC constellations, McRAIM can significantly enhance the detection and exclusion probabilities of two simultaneous faulty satellites in RTK solutions.

Introduction

Global Navigation Satellite System (GNSS) integrity monitoring, for instance, Global Positioning System (GPS) Receiver Autonomous Integrity Monitoring (RAIM) has been investigated for since later 1980’s and already used in safety and liability critical applications such as non-precision approach and road transport management (Brown, 1988, Feng and Ochieng, 2006b, Feng and Ochieng, 2007). The inputs to the RAIM algorithms include code measurements, measurement noise levels, receiver to satellite geometry information. The probabilities for a false alert and a missed detection must also be given, so that the RAIM processor can provide alarm alerts together with the protection levels (Kaplan and Hegarty, 2006). Though there are a few different RAIM algorithms, Brown (1992) has proved that the equivalence between the range-comparison method, least-squares-residual method and parity method. An enhanced version of RAIM employed is known as Fault Detection and Exclusion (FDE), which uses a minimum of six satellites to detect a possible faulty satellite and then exclude if from the navigation solution so the navigation function can continue without interruption, more details about this procedure can be found at (Brown, 1992).

The RAIM concepts and algorithms were initially developed in the context of GPS single point positioning (SPP) solutions, where only the line-of-sight (LoS) pseudoranges are observables (Parkinson and Axelrad, 1988), which has been known as pseudorange-based RAIM (PRAIM). PRAIM algorithms are relatively simple and can easily be adopted in code base differential GPS (DGPS) processing. In general, the RAIM concept, as well as its extended version, such as Fault Detection and Isolation and Fault-Detection and Exclusion (FDE), has been widely accepted in the navigation community and being applied in non-precision navigation and other applications (Ober, 1997, Brown and Chin, 1998, Feng et al., 2006a). Many advanced GNSS receivers are RAIM capable for various navigation applications.

In high precision positioning, such as using real time kinematic (RTK) positioning for liability critical applications, the integrity of the RTK solutions should also be monitored. RTK integrity monitoring is a more complicated problem. The existing PRAIM algorithms cannot be directly adopted in the RTK algorithms, because double-differenced carrier phase measurements for precise positioning are used, and the carrier phase ambiguities must be resolved. Ambiguity Resolutions (AR) includes two procedures: integer estimation and integer search. The complexity of the situation is that outliers and large biases in carrier phase measurements can lead to wrong integer solutions, whilst the existing RAIM algorithms are only adoptable for integer-fixed RTK position estimation processing. In other words, we have to deal with the AR problems and integrity detection simultaneously. This is very challenging especially when the number of satellites is fewer and the satellite geometry is poor.

The early carrier phase based RAIM was the extension of PRAIM algorithms. Once the ambiguities fixed, one can take advantage of the pseudorange RAIM method to detect and isolate the large errors in carrier phase measurements with high accuracy level (Pervan et al., 1996). More recent research efforts involved issues such as ambiguity resolution and validation in carrier-phase RAIM (CRAIM), the failure sources and characteristics, probability of correct fix (PCF) or success rate, test statistic and corresponding threshold (Wu et al., 2008, Khanafseh and Pervan, 2008, Feng et al., 2009). In the mean time, significant research efforts have also been made towards detection and exclusion of multiple failures in multiple GNSS constellations, including the Novel Integrity Optimized RAIM (NIORAIM) method (Hwang and Brown, 2008), extended W-Test and Separability method (Hewitson and Wang, 2006, Ni et al., 2007) and performance benefits of detection and exclusion of simultaneous multiple faults in RAIM algorithm (Feng and Wang, 2006a).

Some preliminary studies have also demonstrated the performance benefit for improved AR success rates and positioning accuracy in carrier phase based RTK positioning (Feng and Rizos, 2008b). On the other hand, once ambiguities are fixed correctly, the integers should remain invariant for the same visible satellites if no cycle slips occur during the observation interval. This invariant nature of ambiguity parameters is useful for RTK integrity determination.

In the near future, with the advent of new GNSS systems, such as Galileo and Compass, the number of satellites in view could be increased by several times. While this can bring significant benefits to the performance of RTK positioning, the risk of multiple fault occurrences will also increase. This paper studies the receiver autonomous integrity monitoring (RAIM) algorithms and performance for RTK solutions with multiple-constellations. The proposed method is generally known as McRAIM, which takes advantage of the ambiguities' invariant character to assist fast identification of multiple faults in the context of multiple constellations. The concept of Virtual Galileo Constellation (VGC) proposed by Feng (2005) is used to create a useful data set for performance analysis. The rest of this paper is organized as follows. Section 2 provides the basic linear models necessary for RTK positioning and integrity detections, including GPS and Virtual Galileo Constellation (VGC) models and RAIM testing statistics. In Section 3, the prerequisites and procedures of the proposed McRAIM method are presented. In Section 4, the experimental results from a 24-h data set over a 21km baseline are discussed, demonstrating a number of distinct performance benefits that multi-constellations can bring to RTK integrity monitoring with respect to the single GPS constellation. The main findings of the paper are summarized in the final section.

Linear Observational Models and LS Solutions

Geometry-based Integer Least Square (ILS) Solutions

With two dual-frequency GPS receivers, one can form two double differenced (DD) carrier phase and code observation equations, respectively:

$$\Delta\nabla\phi_1 = \Delta\nabla\rho + \Delta\nabla\delta_{orbit} + \Delta\nabla\delta_{trop} - \frac{\Delta\nabla I}{f_1^2} - \lambda_1\Delta\nabla N_1 + \varepsilon_{\Delta\nabla\phi 1} \tag{1}$$

$$\Delta\nabla\phi_2 = \Delta\nabla\rho + \Delta\nabla\delta_{orbit} + \Delta\nabla\delta_{trop} - \frac{\Delta\nabla I}{f_2^2} - \lambda_2\Delta\nabla N_2 + \varepsilon_{\Delta\nabla\phi 2} \tag{2}$$

$$\Delta\nabla P_1 = \Delta\nabla\rho + \Delta\nabla\delta_{orbit} + \Delta\nabla\delta_{trop} + \frac{\Delta\nabla I}{f_1^2} + \varepsilon_{\Delta\nabla P1} \tag{3}$$

$$\Delta\nabla P_2 = \Delta\nabla\rho + \Delta\nabla\delta_{orbit} + \Delta\nabla\delta_{trop} + \frac{\Delta\nabla I}{f_2^2} + \varepsilon_{\Delta\nabla P2} \quad (4)$$

In (1) to (4), the symbol $\Delta\nabla$ represents double difference operations between satellites and receivers; ϕ_1 ,and ϕ_2 are phase signals on L1 and L2 frequencies, P1 and P2 are code measurements on L1 and L2 carriers; the symbol ρ is the geometric distance between satellite S and receiver antenna R; δ_{orbit} is the satellite orbital error in meters; δ_{trop} is the tropospheric propagation bias in meters; $\frac{I}{f_1^2}$ and $\frac{I}{f_2^2}$ are the ionospheric propagation errors with respect to L1 and L2 carriers; λ_1 and λ_2 are wavelengths of L1 and L2 carriers; N_1 and N_2 are ambiguities of L1 and L2 carriers; ε_ϕ and ε_p are observation noises of carrier and code respectively.

For a two receiver baseline, optimally combined virtual phase code measurements is suggested to used instead of original signals for more efficient geometry-based AR, based on the minimal total noise level in cycles, which actually reduce the correlation between selected combined DD measurements(Feng, 2008a). For instance, the combined code observable is less noisy over a medium baseline over which the magnitude of code noise may be larger than the effect of ionosphere:

$$\Delta\nabla P_{12} = \frac{f_1\Delta\nabla P_1 + f_2\Delta\nabla P_2}{f_1 + f_2}, \quad (5)$$

One can use the widelane phase measurement

$$\Delta\nabla\phi_{12} = \frac{\cdot f_1 \cdot \Delta\nabla\phi_1 - f_2 \cdot \Delta\nabla\phi_2}{f_1 - \cdot f_2} \quad (6)$$

along with the narrowlane phase measurement

$$\Delta\nabla\phi_{43} = \frac{\cdot 4 f_1 \cdot \Delta\nabla\phi_1 - 3 f_2 \Delta\nabla\phi_2}{4 f_1 - \cdot 3 f_2} \quad (7)$$

to form the observation equation for each baseline:

$$\begin{bmatrix} \Delta\nabla P_{12} - \Delta\nabla\rho_0 \\ \Delta\nabla\phi_{12} - \Delta\nabla\rho_0 \\ \Delta\nabla\phi_{43} - \Delta\nabla\rho_0 \end{bmatrix} = \begin{bmatrix} A_1 & 0 & 0 \\ A_1 & -\lambda_{12} I & 0 \\ A_1 & 0 & -\lambda_{43} I \end{bmatrix} \begin{bmatrix} \delta X \\ \Delta\nabla N_{12} \\ \Delta\nabla N_{43} \end{bmatrix} + \begin{bmatrix} \varepsilon_{\Delta\nabla P12} \\ \varepsilon_{\Delta\nabla\phi12} \\ \varepsilon_{\Delta\nabla\phi43} \end{bmatrix} \quad (8)$$

where A_1 is the design matrix for the user coordinates vector δX, I is identity matrix; and the effects of ionospheric and tropospheric biases were eliminated in the model. Let

$$L = \begin{bmatrix} \Delta\nabla P_{12} - \Delta\nabla\rho_0 \\ \Delta\nabla\phi_{12} - \Delta\nabla\rho_0 \\ \Delta\nabla\phi_{43} - \Delta\nabla\rho_0 \end{bmatrix} A = \begin{bmatrix} A_1 \\ A_1 \\ A_1 \end{bmatrix} B = \begin{bmatrix} 0 & 0 \\ -\lambda_{12} I & 0 \\ 0 & -\lambda_{43} I \end{bmatrix} \Delta\nabla N = \begin{bmatrix} \Delta\nabla N_{12} \\ \Delta\nabla N_{43} \end{bmatrix} e = \begin{bmatrix} \varepsilon_{\Delta\nabla P12} \\ \varepsilon_{\Delta\nabla\phi12} \\ \varepsilon_{\Delta\nabla\phi43} \end{bmatrix} \quad (9)$$

The general geometry-based linear observational equations are expressed as follows

$$L = A\delta X + B\Delta\nabla N + e \quad (10)$$

$$E(e) = 0 \qquad Cov(e) = \sigma_e^e P^{-1} \quad (11)$$

where P is the weight matrix of measurements. The real-value least squares solution of the equation (10) and (11) are given as:

$$\begin{bmatrix} \delta\hat{X} \\ \Delta\nabla\hat{N} \end{bmatrix} = \begin{bmatrix} A^T PA & A^T PB \\ B^T PA & B^T PB \end{bmatrix}^{-1} \begin{bmatrix} A^T PL \\ B^T PL \end{bmatrix} \quad (12)$$

and the covariance matrix is

$$Cov(\begin{bmatrix} \delta\hat{X} \\ \Delta\nabla\hat{N} \end{bmatrix}) = \sigma_0^2 \begin{bmatrix} Q_{\delta\hat{X}} & Q_{\delta\hat{X}\Delta\nabla\hat{N}} \\ Q_{\Delta\nabla\hat{N}\delta\hat{X}} & Q_{\Delta\nabla\hat{N}} \end{bmatrix} = \sigma_e^2 \begin{bmatrix} A^T PA & A^T PB \\ B^T PA & B^T PB \end{bmatrix}^{-1} \quad (13)$$

In the next step, the float solution $\Delta\nabla\hat{N}$ and its variance-covariance matrix are used to compute the corresponding best integer ambiguity estimate, which implies solving the search function

$$(\Delta\nabla N - \Delta\nabla\hat{N})^T Q_{\Delta\nabla\hat{N}}^{-1} (\Delta\nabla N - \Delta\nabla\hat{N}) = \min \quad (14)$$

The LAMBDA method applies to find the solution which will be denoted as $\Delta\nabla\breve{N}$. Finally, the so-called ambiguity fixed estimator of geometry-based ILS solution $\delta\breve{X}$ can be obtained as

$$\delta\breve{X} = \delta\hat{X} - Q_{\delta\hat{X}\Delta\nabla\hat{N}} Q_{\Delta\nabla\hat{N}}^{-1} (\Delta\nabla\hat{N} - \Delta\nabla\breve{N}) \quad (15)$$

Virtual Galileo Constellation (VGC) Model

The concept of VGC is to combine the GPS measurements data sets recorded at two epochs separated by a few hours for form dual constellations for data analysis. Feng (2005) showed that the separation could range from 1 to 2 hours. For GPS and VGC data sets, one can obtain the linear equations based on (10) (Feng, 2005a)

$$\begin{bmatrix} L_{gps} \\ L_{gal} \end{bmatrix} = \begin{bmatrix} A_{gps} & B_{gps} & 0 \\ A_{gal} & 0 & B_{gal} \end{bmatrix} \begin{bmatrix} \delta X \\ \Delta\nabla N_{gps} \\ \Delta\nabla N_{gal} \end{bmatrix} + \begin{bmatrix} e_{gps} \\ e_{gal} \end{bmatrix} \tag{16}$$

It is noted that in (16), two data sets have the same coordinates, but different sets of ambiguity parameters. The ILS solutions can be obtained similarly.

Testing Statistics Based on Least-Squares-Residuals (LSR)

After the integer ambiguities are correctly fixed, one can obtain simplified linear equations as

$$y = A\delta x + e \tag{17}$$

where $y = L - B\Delta\nabla\breve{N}$. The measurements error vector is

$$v = y - \hat{y} = y - A\delta\breve{X} = L - B\Delta\nabla\breve{N} - A\delta\breve{X}\,. \tag{18}$$

From these error estimates, a scalar measure defined as the Weighted Sum of the Squared Errors

$$WSSE = v^T P v \tag{19}$$

can be used as out test statistic to detect potential failures of measurements. In the absence of any failure measurement, $e \sim N(0, \sigma_0^2 P^{-1})$, $WSSE$ follows a central chi-square distribution $\chi^2_{\alpha,dof}$, that is,

$$\frac{WSSE}{\sigma_0^2} \sim \chi^2_{\alpha,dof}\,, \tag{20}$$

where σ_0 is the measurements noise standard deviation, α is the confidence level, and dof is the degrees of freedom. Furthermore, the corresponding detection threshold can be calculated as

$$T = \sigma_0^2 \cdot \chi^2_{\alpha,dof}\,. \tag{21}$$

Hence the following criterion is applied to check whether the system works properly based on a hypothesis testing. As $WSSE$ is constructed to be test statistic and the threshold variable is T, then H_0 is the null hypothesis (no fault) and H_1 is the alternative hypothesis (with fault satellites). Therefore, we have

$$\begin{aligned} H_0 &: \quad WSSE < T \\ H_1 &: \quad WSSE \geq T \end{aligned} \tag{22}$$

The above testing statistic has been used in the PRAIM and many other applications, and is directly adopted here for ambiguity-fixed carrier phase based RAIM. The problem is that the incorrectly fixed integers may not be detectable in the above test statistic. For instance, certain phase measurement errors, such as cycle slips, can be masked or absorbed into ambiguity solutions, which could result in wrong RAIM decisions. The next section proposes a new RAIM scheme to address the problems more generally.

Multiple-Constellation RAIM (McRAIM) for RTK Positioning

Detecting and excluding failures or outliers in DD carrier phase based RTK solutions are challenging. Table 1 compares pseudorange-based navigation and carrier phase based RTK positioning, showing the complexity of RTK problem with respect to a navigation problem. Firstly, the RTK deals with DD measurements, each DD involves four satellites. Secondly, each DD phase measurement has an integer ambiguity parameter. In RTK estimation problem, RTK involves both least-square estimation and ambiguity search procedures. The challenge also lies in that in PRAIM, inclusion of the measurements with small undetected outliers may not result in the position solutions worse than excluding the satellite. But in the RTK case, a centimeter error placed on certain satellites could cause a large number of wrong integer solutions, thus leading to totally wrong position solutions. This can be evident from a simple example as shown in Figure 1, showing the effects of added 0.1 cycle errors to two DD L1 phase measurements on the actual 3D positional results after the integers are fixed (upper plot) and the same errors on the L1 carrier before AR process (lower plot). The details of the data sets used and computation schemes in the example are referred to next section.

Additional insights into a GPS RTK problem are summarized as follows:

(1) If there are no cycle slips between two consecutive epochs, the ambiguity integers for the same DD sets should remain unchanged. This nature can be used for effective integrity determination.

(2) For the same DD sets, if the integers obtained from the current epoch are inconsistent with their previous solutions, these ambiguity solutions may likely be wrong.

(3) If the integer solutions between two epochs remain the same for the same data sets, one still cannot guarantee that all the integers of the current epoch are correct and there are zero faulty satellites.

(4) Large pseudorange errors can also affect the AR performance.

(5) Integer least squares (ILS) involving integer search is time consuming. The larger the number of DD integer parameters, the longer the ILS process will take.

(6) Large pseudorange errors can also affect the AR performance.

(7) In the dual or multiple satellite constellations, there could be two satellites in the same line of sight, which can potentially cause AR problems.

Table 1 Comparison of navigation and RTK complexity

	Pseudorange (navigation)	Carrier phase RTK
Measurements	Pseudoranges Line of sight (LOS) or single difference (SD)	Pseudoranges and carrier phase double differenced (DD)
Parameters	3D position and 1D clock parameters	3D position and 2M integer ambiguities
Estimation	Least-squares estimation (LSE)	Least-squares estimation (LSE) Integer search
Errors that can causes failures	several meters, especially with poor satellite geometry	a few centimeters, especially with poor satellite geometry
Complexity	Low and Medium	High

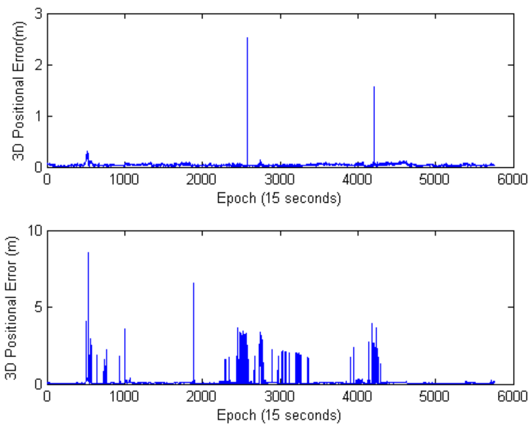

Figure 1. Illustration of the effects of added 0.1 cycle errors to two DD L1 phase measurements on the 3D positional solutions after the integers are fixed (the upper plot) and the same errors to the L1 carrier before AR process (the lower plot).

Based on the above observations, the overall design of Multi-constellation RAIM (McRAIM) is schematically illustrated in Figure 2, comprising four processing modules. The first module performs satellite geometry check, which identifies the satellites from two constellations whose line of sights vectors are significantly closer than these with all others. These LoS collided satellites will be flagged and only one of these satellites should be entered in the follow-on PRAIM processing. PRAIM process aims to detect and exclude up to 3 satellites of large pseudorange errors using the SD pseudo-range measurements between receivers.

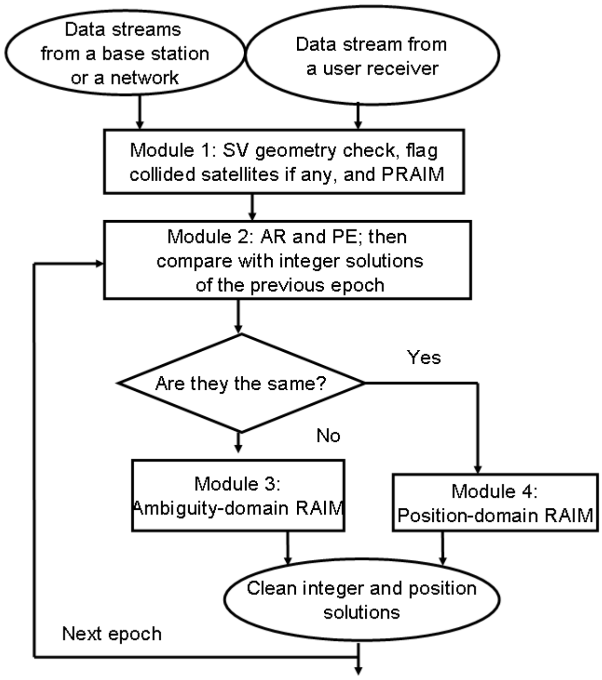

Figure 2. Diagram of Multi-constellation RAIM.

Module 2 is a RTK processor, which performs AR and PE using code and phase measurements from the current epoch only, whose integer solutions are to be compared with these from the previous epoch for the same common visible satellites. If the reference satellite is changed, there is a need to transform the DD ambiguities to a new set with the same reference satellites. Table 2 shows an example of the transformation cases, where the reference satellite is changed from PRN 6 to PRN 30, the new set of DD ambiguities is obtained via the operation of a transformation matrix.

If there are some inconsistent DD integers, McRAIM proceeds to Module 3, which excludes the relevant satellites one by one, then two by two, and re-forms the DD sets and performs AR again with the remaining satellites. If comparison with the integer solutions of the previous epoch for the same DD set shows consistency, the excluded satellites are then identified as the faulty satellites. Otherwise, the excluded satellite measurements were put back and exclude another group of satellites. The AR comparison between two consecutive epochs starts with exclusion of the satellites with inconsistent DD integer solutions. After having gone through all these satellites, if the faulty satellites still cannot be located, then we proceed to deal with the rest of satellites. For all the DD measurements with the consistent integer solutions, the McRAIM proceeds to the next module.

Table 2 Example of DD ambiguities transformation with same reference satellite

PRN List:	6 29 30 18 26 16 7
DD ambiguity set with reference SV PRN 6:	-1101776 -539824 1126158 -512885 -1164238 708027
DD ambiguity set with reference SV PRN 30:	539824 561952 1665982 26939 624414 1247851
Transformation matrix :	$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ -1 & -1 & -1 & -1 & -1 & -1 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$

Module 4 detects and excludes a few possible outliers with ambiguity fixed phase measurements in the position domain. Using the WSSE statistic given in Section 2, the position-domain RAIM is a multiple fault detection and exclusion (MFDE) processor. To test a potential group of faulty SVs, the module deletes every group of SVs and re-forms the DD sets with remaining SVs, and tests the WSSE statistics. The process starts with the case of a single faulty satellite, then proceeds to the cases of 2 and 3 faults, until the null hypothesis is accepted.

Experimental Results

The objective of the experimental analysis is to show how the proposed McRAIM scheme works and demonstrate preliminarily the performance of McRAIM in the context of multiple constellations. A 24 hour GPS data set collected at two CORS sites (P474 and P478) from www.cors.ngs.gov on Day 1 2007 was used in the analysis. The GPS&VGC data sets of 24 hour for the same baseline is then generated for experimental analysis with the McRAIM procedures. For this 21 km baseline, the data is basically clean and normal, and can thus provide integer and position solutions for reference. The set ups of the three computation scenarios are given as follows:

Scenario 1: Process both GPS and GPS&VGC data sets without adding errors and performing RAIM function.

Scenario 2: Process both GPS and GPS&VGC data sets with adding errors of 0.5 cycles on the 3rd and 5th SVs over the whole data period, but without performing the RAIM function.'

Scenario 3: Process both GPS and GPS&VGC data sets with adding errors of 0.5 cycles on the 3rd and 5th SVs over the whole data period like Scenario 3, but performing the RAIM function.

Figure 3 plots the XYZ position errors obtained from Scenario 1. It shows that in GPS alone case, the positioning results at epochs 2573 and 4207 are wrong, due to the wrong ambiguity solutions. In the GPS&VGC case, the position errors fall into the range of $\pm 0.05m$. Figure 4 plots the RMS values of unit weight for both two cases. It shows that in the dual constellation, that is GPS &VGC case, the fluctuation of RMS is smaller than that of the GPS case, due to the higher measurement redundancy.

Next we examine the effects of adding errors to two satellites and McRAIM performance in both single- and dual-constellation cases. Figure 5 shows the XYZ position errors obtained from the GPS data alone in Scenario 2 and Scenario 3. From these plots, it is clearly observed that the two added half cycle errors have seriously affect the ambiguity solutions, resulting in totally wrong position solutions in almost all the time epochs. This is an indication of the significance of integrity monitoring in RTK solutions. With the McRAIM procedures, two added errors could be detected and excluded only over time epochs. This shows that the delectability of McRAIM in the GPS case alone is limited.

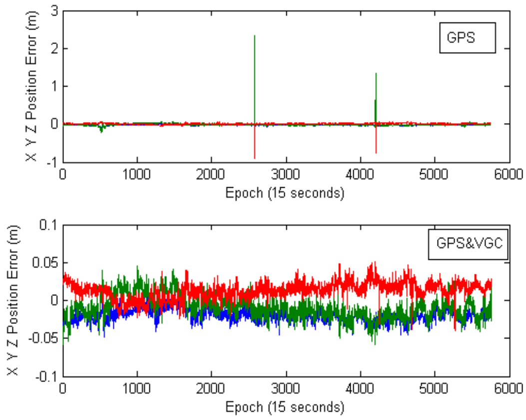

Figure 3. Illustration of the actual XYZ errors obtained from GPS and GPS&VGC constellations, respectively.

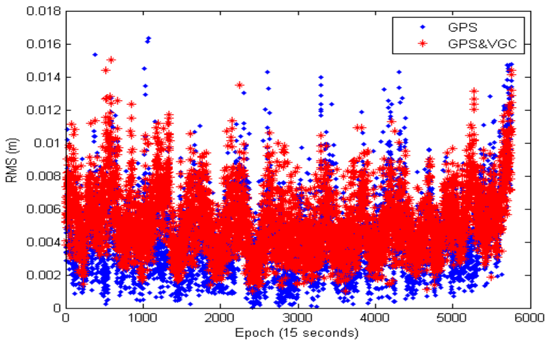

Figure 4. Plots of RMS values obtained with the GPS and GPS&VGC constellations respectively

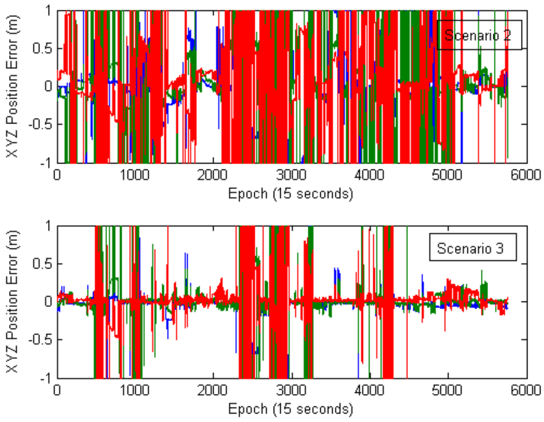

Figure 5. Illustration of the XYZ errors obtained from the GPS data alone in Scenario 2 (upper) and Scenario 3 (lower).

Figure 6 shows the XYZ coordinate errors obtained from Scenario 2 and Scenario 3 for the case of GPS&VGC constellation. As shown, added errors to two satellites also cause the ambiguity solutions to fail even in the GPS&VGC constellation. But, after applying McRAIM, the fault added satellites are excluded and the positioning results are remarkably ameliorative and become as good as those in Scenario 1: the positional errors fall within the range of $\pm 0.05m$.

Figure 7 gives the RMS values of three scenarios in GPS and GPS&VGC cases respectively. As the upper plot of Figure 8 shows, with the GPS constellation alone, it is difficult to distinguish between three RMS solutions. In the GPS&VGC case, RMS values from Scenario 2 are clearly distinct from Scenario 1 and Scenario 3. It implies that in the GPS&VGC case, RMS values or their equivalent statistics could be effective for detection of satellite failures.

In Figure 8, the faulty satellites identified in the McRAIM process are marked in the sequence of SVs. That is, SV 2 represents the 2nd SV that the processing software picked up from the rover RINEX data. Value 0s represents the case when no SVs are excluded, meaning that the exclusion of the faulty satellites are missed out. The correct answers are the 3rd and 5th SVs to which errors were added as mentioned previously. In the cases where other SVs are marked, the system mistakenly excludes at least one non-faulty satellite. The figure clearly illustrates the McRAIM performance benefits of the dual-constellation with respect to a single constellation.

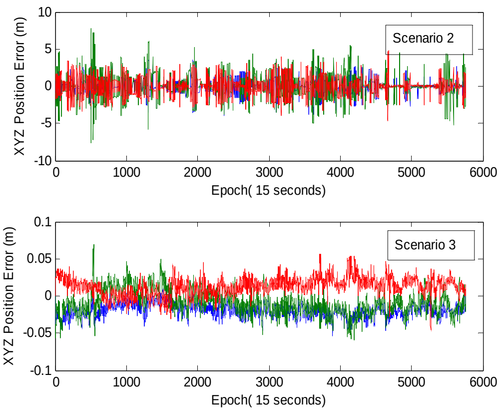

Figure 6. Illustration of the XYZ coordinate errors obtained from Scenario 2 and Scenario 3 for the GPS&VGC constellation.

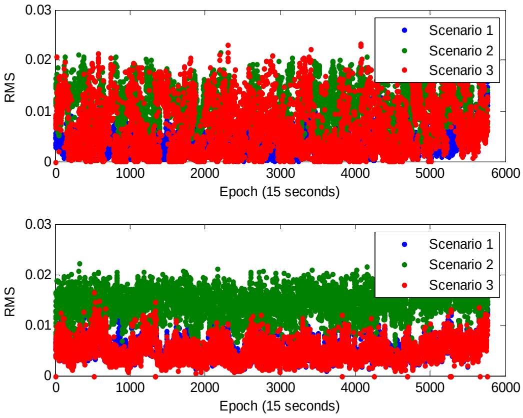

Figure 7. Illustration of the RMS estimates from three computing scenarios with the GPS& VGC constellation.

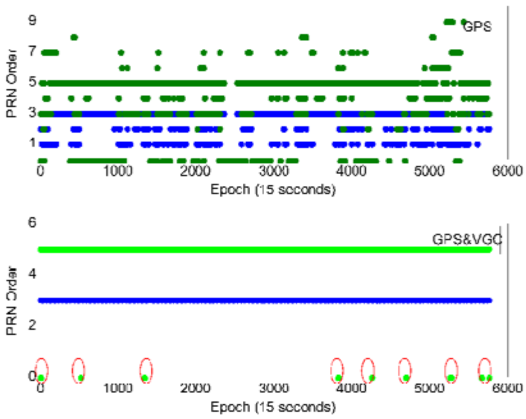

Figure 8. Illustration of detected faulty satellites SV sequence.

Table 3. Statistical results from the GPS&VGC constellation with two failures

	GPS	GPS&V`GC
Overall RMS, Scenario 1	0.0042m	0.0052m
Overall RMS; Scenario 2	0.0107m	0.0144m
Overall RMS, Scenario 3	0.0069m	0.0050m
Missed detection	110	0
Wrong exclusion	1529	0
Invalid exclusion	565	25
Rate of correct detections	98.07%	100%
Rate of correct exclusions	62.94%	99.57%

Table 3 gives the overall results of McRAIM performance in the GPS and GPS&VGC constellations, which are discussed as follows.

- The RMS values obtained from Scenario 2 are distinctly larger than these from other two scenarios. This is especially true with the GPS& VGC case, implying that the RMS or its equivalent quantities can be effective testing statistics for fault detections.

- Regarding the performance of detection and exclusion, there are no missed detections and wrong exclusions and just 25 invalid exclusions in the dual-constellation case, as opposed to 110 missed detections, 1529 wrong exclusions and 565 missed exclusions in the GPS case. This confirms that the significant performance benefits of the GPS& VGC with respect to the GPS alone.

- Overall, the McRAIM performance in terms of faulty detection and exclusion power in the GPS&VGC case is much higher than those in the GPS case.

Conclusions

This paper has developed a new RAIM method for detection and exclusion of multiple faults in multi-constellations to cater for the next generation of GNSS. In the near future, with the advent of new GNSS systems, such as Galileo and Compass, the satellites in view could be increased by several times. This could introduce the risk of multiple fault occurrences, while bring performance improvement to precise positioning. The proposed scheme takes advantage of ambiguity invariant character to identify multiple failures in multi-constellations in the ambiguity search and position estimation processes respectively. Dealing with multiple failures is a difficult task in single navigation system due to limitation of visible satellites and geometry. However, the experimental results from a real GPS data set of 21km baseline have shown that in the case of multiple constellations, it is not only possible to detect the two failures but also to exclude these failures in the probability of 99.57%. Although extensive experimental analysis is on-going to examine the McRAIM delectability for smaller outliers and systematic errors, the overall McRAIM design is shown to be effective and promising for RTK integrity determination in multiple GNSS constellations.

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